Role of Transpiration Reduction during Center Pivot Sprinkler Irrigation in Application Efficiency

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ABSTRACT

The magnitude and duration of corn transpiration reduction during center pivot sprinkler irrigation was analyzed on a commercial plot. The irrigation event was defined as the period during which the pivot arm was passing over a transect AC and water droplets were moistening the plants (*moist* treatment, MT). Corn transpiration rates were measured at three spots of that transect, and, simultaneously, at another spot (*dry* treatment, DT) located about 270 m east from the transect AC. Corn transpiration rates for MT were reduced by 30 to 36% compared to DT during the irrigation event. After irrigation, the transpiration reduction lasted for 1.8 to 2.6 h, and

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ranged from 22 to 29%. The gross wind drift and evaporation losses ranged from 10 to 13 % of the applied water, while the net interception losses were 2% of the applied water. Considering the observed corn transpiration reduction during and after the irrigation, the net sprinkler evaporation losses ranged from 11 to 13% of the applied water, with no relevant differences along the pivot arm.

KEYWORDS

Transpiration reduction; Center pivot; Sprinkler irrigation; Water losses; Application efficiency.

1. INTRODUCTION

The search for efficiency in irrigation is one of the most important issues in irrigated agriculture due to the water scarcity and to the increase in food demand. For field crops such as alfalfa (*Medicago sativa* L.), corn (*Zea mays* L.) and winter cereals, sprinkler irrigation systems are adequate because they allow accurate scheduling of irrigation and can attain high potential efficiency with an adequate cost. Two types of sprinklers irrigation systems can be installed in the field: static and movable. Within the movable systems, the linear move laterals and the center pivots are the most important (Tarjuelo et al. 1999).

The use of center pivot systems has increased by more than 50% from 1986 to 1996 in USA (Evans 2001). This growth continues in many irrigated areas around the world due to low investment costs per irrigated hectare, low energy and labour requirements, possibility of applying agrochemicals, high degree of automation and their adaptability to different field topographies and soil textures (Allen et al. 2000).

Many factors affect the uniformity and irrigation efficiency of sprinkler systems which may decrease the net water application efficiency and therefore the crop yield. Some factors are technical, such as the design (spacing and height of sprinklers, nozzle number and size) and management of irrigation facilities (working pressure) (Tarjuelo 1999). Environmental conditions, such as high wind speed, increase the wind drift and evaporation water losses (WDEL), which are the fraction of water droplets emitted by the sprinkler nozzles that do not reach the soil or crop being irrigated. There are also interception water losses (IL), which is the fraction of the water emitted by the sprinklers that is intercepted by crop leaves and stems and it is evaporated before reaching the soil. WDEL and IL can be summed up to get the sprinkler evaporation losses (SEL) (Martínez-Cob et al. 2008).

For solid-set sprinkler irrigation systems, several authors have reported that WDEL range between 0 to 20% of water applied, with greater losses during daytime irrigation (Yazar 1984; Kincaid et al. 1996; Dechmi et al. 2003; Playán et al. 2005; Martínez-Cob et al. 2008). During some particularly windy irrigation events WDEL as high as 30 to 50 % have been reported (Playán et al. 2005). For center pivot systems, Steiner et al. (1983a) reported WDEL of 15% of water applied, while Ortiz et al. (2009) reported WDEL values of 3 to 8 % during nighttime irrigations and 8 to 14 % during daytime irrigations for center pivot systems using rotating or fixed spray plate sprinklers. However, IL depends mostly on the water storage capacity of a crop canopy which is a function of crop architecture. Gross IL include the stored water in the crop canopy during sprinkler irrigation. Thus, Norman and Campbell (1983) and Steiner et al. (1983a) reported storage capacity values (gross IL) for corn ranging between 0.4 and 2.7 mm. Martínez-Cob et al. (2008) reported net IL of 0.3 mm for corn. Net IL was computed as the gross IL minus the transpiration reduction after the irrigation event.

During sprinkler irrigation the vapour pressure deficit (VPD) and temperature of the air within the crop canopy decrease due water evaporating from soil and leaf surfaces (Robinson 1970; Steiner et al. 1983b; Tolk et al. 1995; Cavero et al. 2009). This decrease of VPD during the irrigation reduces crop transpiration and evapotranspiration (ET), leading to the conservation of soil water, which would otherwise be depleted by the crop (Mc Naughton 1981; Steiner et al. 1983a). McNaughton (1981) argued that any reduction in crop ET and transpiration from a wetted area as compared with a dry area (i.e. an area not being irrigated at the same time but kept in the same conditions, including water availability) can be subtracted from the gross irrigation water losses, resulting in the net irrigation water losses. In other words, the part of SEL replacing crop ET should be regarded as beneficial. This leads to the introduction of gross (SEL_g, i.e. the sum of gross WDEL and IL) and net sprinkler evaporation losses (SEL_n, i.e. the sum of net WDEL and IL). Consideration of net evaporation losses instead of gross evaporation losses would result in an increase of application efficiency for a given application depth. This should be taken into account when calculating crop irrigation requirements.

Several studies have analyzed the differences in ET rates between wet and dry surfaces just after irrigation events, but very few have analyzed them during the events themselves. For solid-set sprinkler irrigation, Frost and Schwalen (1960) reported an almost complete suppression of ET while Sternberg (1967) and Martínez-Cob et al. (2008) reported an average reduction of 33 % for rye-grass and corn, respectively. Thompson et al. (1993) used modelling to forecast an evapotranspiration decrease of 40% for corn during solid-set irrigation events. For linear move sprinkler irrigation systems, a reduction of ET has also been observed (Wiersma 1970; Kohl and Wright 1974). Tolk et al. (1995) reported a corn transpiration reduction of 32%, somewhat smaller than the 58 % reported by Martínez-Cob et al. (2008) for solid-set sprinkler irrigation. Thompson et al. (1997) modelled and measured transpiration and ET rates during irrigation events using linear move sprinkler irrigation systems, and showed a transpiration decrease during the irrigation events of about 80 %. To our knowledge, no previous works have reported field measurements of the changes in ET and plant transpiration during irrigation at the different pivot arm portions of a center pivot system.

The aim of this work was to analyze the reduction of plant transpiration during sprinkler irrigation events of corn (*Zea mays* L.) with a center pivot and how much it would contribute to increase the irrigation application efficiency. The magnitude and duration of the reduction of transpiration along different segments of a transect of the center pivot system were assessed.

2. MATERIAL AND METHODS

The experiment was performed from July to September 2008 at a commercial corn field located in Valfarta (Huesca, NE Spain). Geographical coordinates were 41º33'N latitude and 0º07'W longitude; elevation was 354 m above sea level. The long-term yearly averages of total precipitation and mean air temperature in the area are 400 mm and 14.3º C, respectively. The field was planted with the cultivar Pioneer PR34N44 on 15 April 2008, the plant density at harvest was 68000 plants ha^{-1} and the row spacing was 0.75 m. All agronomical practices (irrigation, fertilization and herbicide applications, etc.) were performed according to the farmer's technical criteria. The soil is classified as Typic Torrifluvents and the texture is silty loam.

The field occupied an area of 32.3 ha and was irrigated by a center pivot with impact sprinklers located in the top of the main pivot pipe. The total length of the pivot lateral was 322 m and it was divided into six spans (49.4 m length each) and a final overhang of 25.6 m length (Table 1). The diameter of the main pipe was 0.163 m. All sprinklers had a pressure regulator (Model PSR30, Senninger Irrigation Inc., Clement, FL, USA). Table 1 lists the number of sprinklers and nozzles, the corresponding nozzle diameters, and the spacing between the sprinklers.

The measurements were performed in three spots of the transect AC running from north-northeast to the central axis of the pivot, corresponding to pivot arm portions 2, 4, and 5 (Fig. 1). An additional spot D, located about 270 m east from the transect AC, was also monitored. This spot D was irrigated about 8 hours before the pivot arm moved over the transect AC. The center pivot was almost continuously irrigating the field and it took about 31 h to complete a turn. In this work, a monitored irrigation event was the period that took the pivot to run over a distance of 18 m, 9 m either side of the transect AC. This value of 9 m was established by visual inspection of the moistening radius of the pivot sprinklers at the catch can height previously to the measurement period. Seven irrigation events were monitored in this work. Two treatments were established during each monitored irrigation event: a) *moist* treatment, measurements taken in the transect AC; b) *dry* treatment, measurements taken at the same time in the spot D.

The sprinkler irrigation pressure was continuously measured using pressure transducers (Model 2200/2600, Gems Basingstoke, Hampshire, UK) placed in the last sprinkler of pivot arm portions 2, 4 and 5 (Fig. 1). The pressure transducers were placed between the pressure regulator and the sprinkler, and were connected to loggers (Model Dickson ES120) which stored instantaneous pressure values every 5 minutes. The average of these values (P_i, kPa) during each monitored irrigation event was used to compute the irrigation water depth applied (I_s, mm) for a given pivot arm portion during the monitored irrigation events assuming that all sprinklers of that pivot arm portion had a pressure equal to P_i. For this computation, the following expression based on the Torricelli's Theorem and the Orifice Equation (Norman et al. 1990) was used:

$$I_s = \frac{0.00035\,\pi\,c_d\,P_i^{0.5}\,S_b^2\,T_p}{A_s} \qquad (1)$$

where: c_d is the discharge coefficient, 0.98 (Playán et al. 2005); T_p is the time (s) to complete a turn; A_s is the surface area (m^2) irrigated by the sprinklers of the tower; the corresponding surface area for pivot arm portions 2, 4 and 5 were 23177, 53887 and 69242 m^2. For sprinklers with two nozzles, $S_b^2 = d_l^2 + d_s^2$, where d_l is the large nozzle diameter (mm); d_s is the small nozzle diameter (mm); for sprinklers with one nozzle, $S_b^2 = d_n^2$, where d_n is the nozzle diameter (mm).

T_p (in s) was determined for each pivot arm portion as follows:

$$T_p = 3600 \frac{2\pi \cdot r}{\omega} \qquad (2)$$

where: r is the radius of the pivot at the end of the evaluated pivot arm portion (m); ω is the angular speed of the pivot (m h^{-1}) computed from the time it took to the pivot to run along the distance of 18 m; this time was determined by visual inspection.

A line of 50 plastic catch cans (AITIIP, Zaragoza, Spain) was placed along the transect AC at a spacing of 3 m to collect the irrigation water depth that was used to determine the gross wind drift and evaporation losses ($WDEL_g$) for pivot arm portions 2, 4 and 5. The catch cans were conical in its lower part (200 mm length) and cylindrical in its upper part (100 mm length); the diameter of the upper part was 160 mm. The catch cans were marked in mm for direct readout up to 45 mm. The catch cans were placed just above the crop canopy, and they were moved up as the crop grew along the season. The maximum catch can height was about 2.5 m. Just after the pivot has moved beyond the transect AC, the water depth at each can was read. The water collected in the catch cans was measured immediately after the irrigation event finished in each pivot arm portion. The values of the cans corresponding to each pivot arm portion were averaged to get the mean collected water depth I_{cc} (mm). Then $\mathrm{WDEL_g}$ expressed in mm, was determined as:

$$\mathrm{WDEL_g} = \mathrm{I_s} - \mathrm{I_{cc}} \qquad (3)$$

and $\mathrm{WDEL_g}$, expressed in percentage, was determined as

$$\mathrm{WDEL_g} = \frac{\mathrm{I_s} - \mathrm{I_{cc}}}{\mathrm{I_s}} 100 \qquad (4)$$

Three meteorological stations were installed at the transect AC (stations A, B and C, respectively) and a fourth meteorological station (station D) was installed at spot D (Fig. 1) to measure the microclimatic changes due to sprinkler irrigation. Each meteorological station was equipped with a datalogger (model CR10X, Campbell Scientific, Logan, UT, USA) that monitored a probe for air temperature and relative humidity (model HMP45C, Vaisala, Helsinki, Finland). The HMP45C probe was installed at 2.9 m above ground and its accuracy was of ± 0.3ºC for air temperature and ± 2% for relative humidity. The air temperature and relative humidity were measured each 10 s and the 5-min averages of these two variables were continuously recorded. The 5-min values of vapour pressure deficit (VPD) were calculated from the recorded values of air temperature and relative humidity following Allen et al. (1998). The meteorological station installed at the spot D had also a cup anemometer (Vector Instruments, model A100R) and a net radiometer (Kipp & Zonen, model NR-Lite) located at about 3.0 m above ground. Data collected by both sensors were also monitored each 10 s and the corresponding 5-min averages of wind speed and net radiation were recorded by the datalogger through the season.

During each monitored irrigation event, corn plant transpiration rates were measured every 10 minutes from 2 h before to 6 h after the pivot moved over the transect AC (Fig. 1) taking into account the different duration of the irrigation events at the measurement spots A to C (Table 3). In other words, the total measurement period during each irrigation event was different at each spot. The transpiration rates were determined from sap flow measurements using the heat balance method (Baker and van Bavel, 1987; Weibel and Boersma, 1995; Van Bavel 2005). This method was chosen because it had been previously used on corn in similar studies to this (Tolk et al. 1995; Martínez-Cob et al. 2008). At each spot, a Flow4 datalogger (Dynamax, Houston, USA) was installed to monitor, log and process data collected by four sap gauges SGB19 (Dynamax) each of them installed in a plant. These gauges are appropriate for stems of 18-23 mm in diameter. The sap gauges were moved to a second set of four plants within the same area of the field on July 25 and 14 August of 2008 to avoid any possible damage to the plants (Van Bavel 2005). Each gauge had a soft foam collar surrounding the electronics. In addition, once installed in the plant, each gauge was surrounded by a weather shield (aluminium bubble foil) such it held a cylindrical shape. The aluminium top shield was secured using insulation tape. The shield kept out water and prevented radiation from affecting readings (Van Bavel, 2005). Following this author, the datalogger was set to apply a continuous average voltage of 4.0 V while the heater resistance of the different gauges varied between 58.9 to 64.6 Ω. Van Bavel (2005) thoroughly describes the elements of the gauges, the electronics, the recorded values and the equations used to process them to obtain transpiration rates at each gauge. The transpiration rates at each spot before, during and after the pivot moved over the transect AC, were determined as the average of those obtained from the four sampled plants per spot. These average transpiration rates were determined in grams per hour and transformed into millimeters per hour using the average number of plants m^{-2} measured at each spot (6.8 plants m^{-2}).

During each monitored irrigation event, the differences in corn transpiration rates between the moist and dry treatments were computed for pivot arm portions, 2, 4 and 5. These differences allowed establishing different periods before, during and after each irrigation event for each pivot arm portion: 1) B1, before the irrigation event, when the difference between the individual 10-min values of both treatments was below the resolution of the sap gauges, 0.1 mm h^{-1}; 2) B2, before the irrigation event, when the difference between the individual 10-min values of both treatments was greater than 0.1 mm h^{-1}; 3) Du, during the irrigation event; 4) A1, after the irrigation event, when the difference between the individual 10-min values of both treatments was greater than 0.2 mm h^{-1}; 5) A2, after the irrigation event, when the difference between the individual 10-min values of both treatments was between 0.1 and 0.2 mm h^{-1}; and 6) A3, after the irrigation event, when the difference between the individual 10-min values of both treatments was less than 0.1 mm h^{-1}. In some cases, the differences between the individual 10-min values of both treatments did not meet the criteria to establish the phases B2 and A1 for a particular pivot arm and irrigation event. The computed values of air VPD were also grouped for analysis according to the abovementioned phases for analysis of corn transpiration. For each phase and pivot arm portion, the corn transpiration rate and air VPD of the moist and dry treatments were compared using a paired t test and a level of significance of $P = 0.05$.

Following Martínez-Cob et al. (2008), the net sprinkler evaporation losses (SEL_n) for the center pivot system of this study were estimated as:

$$SEL_n = WDEL_n + IL_n \tag{5}$$

where $WDEL_n$ and IL_n are the net wind drift and evaporation losses and the net interception losses, respectively. The $WDEL_n$ of the center pivot of this study were estimated as the difference between $WDEL_g$ and the reduction of evapotranspiration due to the irrigation, i.e. that occurring before (period B2) and during (phase Du) the sprinkler irrigation events (McNaughton 1981; Martínez-Cob et al. 2008):

$$WDEL_n = WDEL_g - (ET_{red})_{di} \tag{6}$$

where $(ET_{red})_{di} = (ET_{DT} - ET_{MT})_{di}$ is the reduction of evapotranspiration due to irrigation (di); ET_{DT} and ET_{MT} are the evapotranspiration rates in the treatments dry and moist, respectively, during the irrigation events.

In this work, transpiration rates were measured instead of evapotranspiration rates. Martínez-Cob et al. (2008) showed that the average reductions of evapotranspiration (measured with a weighing lysimeter) and transpiration (measured with sap flow gauges) during solid-set sprinkler irrigation of corn were 32% and 58%, respectively. Because the crop and climatic conditions of this work were similar to those of Martínez-Cob et al. (2008), it was assumed, as a first rough approximation, that the ratio transpiration to evapotranspiration reduction (0.559) reported by those authors could be used to estimate the reduction of evapotranspiration due to irrigation (phases B2 and Du) in this work. Further studies should be performed to determine a ratio of transpiration to evapotranspiration reduction more appropriate for center pivots. Thus,

$$(ET_{red})_{di} = 0.559\,(T_{red})_{di} \qquad (7)$$

where $(T_{red})_{di}$ = $(T_{DT} - T_{MT})_{b2}$ + $(T_{DT} - T_{MT})_{du}$, being $(T_{DT} - T_{MT})_{b2}$ the reduction of transpiration before irrigation (phase B2) and $(T_{DT} - T_{MT})_{du}$ the reduction of transpiration during (phase Du) the center pivot irrigation events; T_{DT} and T_{MT} are the transpiration rates in the treatments dry and moist, respectively, before and during the irrigation events.

The IL_n of the center pivot system of this study were estimated as:

$$IL_n = (ET_{MT})_{ai} - (ET_{DT})_{ai} \qquad (8)$$

where $(ET_{MT})_{ai}$ – $(ET_{DT})_{ai}$ is the increase of evapotranspiration in the moist treatment after (ai) the sprinkler irrigation events; $(ET_{MT})_{ai}$ and $(ET_{DT})_{ai}$ are the evapotranspiration rates in the treatments moist and dry, respectively, after the irrigation events. This increase of evapotranspiration after the irrigation is the net balance between the increase of evaporation of intercepted water (gross interception losses, IL_g) and the reduction of transpiration that occurred some time after the irrigation (McNaughton 1981; Tolk et al. 1995; Martínez-Cob et al. 2008). Martínez-Cob et al. (2008) reported that $(ET_{MT})_{ai}$ was about 35 % greater than $(ET_{DT})_{ai.}$ Because IL_g depend mostly on the water storage capacity of a crop (Norman and

Campbell 1983; Steiner et al. 1983a) and the climatic and cropping conditions in this work were similar to those of Martínez-Cob et al. (2008), it was assumed that $(ET_{MT})_{ai}$ was roughly 35 % greater than the estimated $(ET_{DT})_{ai}$ obtained from the data recorded in the meteorological station at the spot D (see Appendix A). Again further research should determine more appropriate values of these evapotranspiration rates for central pivots. Thus, IL_n was estimated as:

$$IL_n = 1.35\,(ET_{DT})_{ai} - (ET_{DT})_{ai} \quad (9)$$

Finally, half-hour values of several meteorological variables (wind speed and direction, solar radiation, air temperature, and relative humidity) were collected to characterize the general standard meteorological conditions occurring during the monitored irrigation events. These values were recorded at a standard weather station located over grass following Allen et al. (1998) guidelines (‘grass station’) about 3 km southeast from the experimental plot. This station belongs to a network named SIAR installed and managed by the Spanish Ministry of Natural, Rural and Marine Environment (MARM, 2011).

3. RESULTS AND DISCUSSION

There were some differences between the meteorological conditions recorded at the ‘grass station’ during the irrigation events at the different dates (Table 2). The overall mean temperature during the irrigation events (phase Du) was 27.8ºC, but the average temperatures ranged between 22.8 °C (13 August) and 32.5 ºC (31 July). The cooler irrigation event (13 August) was also the windiest, while the hottest irrigation event (31 July) showed the highest vapour pressure deficit of the air (3.6

kPa). The $WDEL_g$ are highly affected by the meteorological conditions, particularly wind speed and vapour pressure deficit (Playán et al. 2005, and references therein). Therefore, the observed differences on the meteorological conditions could explain some of the differences found for $WDEL_g$ between the monitored irrigation events as discussed below. No precipitation was recorded neither during nor just before or just after the monitored irrigation events.

On average it took about 30.8 h for the pivot to complete a turn. The starting time for the irrigation was about the same for all monitored irrigation events and ranged from 8:25 to 10:30 Greenwich Mean Time (Table 3). The duration of the irrigation event along the transect AC in the different monitored pivot arm portions decreased as the distance to the center of the pivot increased (Table 3). On average, the transect AC was irrigated during 1.6 h (pivot arm portion 2), 0.6 h (pivot arm portion 4) and 0.5 h (pivot arm portion 5). The average irrigation pressure in these three pivot arm portions along the monitored irrigation events was 197 kPa (coefficient of variation, CV, of 3%). This low CV value indicated a quite constant irrigation pressure during the irrigation events. On average, the irrigation pressure in the pivot arm portion 2 was slightly greater (210 kPa) than that in the pivot arm portions 4 (190 kPa) and 5 (192 kPa) (Table 3). The average applied water in the three monitored pivot arm portion was quite similar: 14.4 (pivot arm portion 2), 13.3 (pivot arm portion 4), and 14.1 mm (pivot arm portion 5) (Table 3).

The time evolution of the 10-min transpiration rates and air VPD recorded at the two treatments since 2 h before until 6 h after the irrigation event of 31 July is shown in Fig. 2. These results are representative of those observed in the rest of irrigation events. Before the irrigation, phase B1, the transpiration rates and air VPD for both treatments were similar. As the pivot arm was arriving near the transect AC, the transpiration rates and air VPD for the moist treatment decreased compared to those for the dry treatment (phase B2). This decrease was greater during the irrigation event (phase Du) and remained similar some time after the irrigation (phase A1). After that, the transpiration rates and air VPD for both treatments became closer and finally were similar during the phase A3. In general terms, this time evolution of the transpiration rates and air VPD observed at the two treatments during (phase Du) and after (phases A1 and A2) the irrigation events was similar to that described in previous works of sprinkler irrigation (Thompson et al. 1993; Tolk et al. 1995; Liu and Kang 2006; Martínez-Cob et al. 2008; Cavero et al. 2009). However, in this current work, the decrease of transpiration rates and air VPD for the *moist* treatment was observed just before (phase B2) the beginning of most monitored irrigation events. The existence of this phase is discussed later.

For all irrigation events, the values of air VPD recorded for the two treatments before irrigation (phase B1) were similar and the average difference did not exceed 0.08 kPa (Fig. 3, Table 4). This difference although significant was within the expected accuracy of the air VPD computations according to the accuracy of the air temperature and relative humidity measurements. The average differences between treatments gradually increased just before and during the irrigation: 0.18 to 0.24 kPa (15.0 to 18.3%) during the phase B2, and 0.54 to 0.68 kPa (38.0 to 49.3%) during the phase Du (Fig. 3, Table 4). After the irrigation events, the average differences between treatments become gradually smaller: 0.36 to 0.45 kPa (20.7 to 26.8 %)

during the phase A1, 0.17 to 0.20 kPa (8.4 to 9.1 %) during the phase A2, and, finally, 0.08 to 0.10 kPa during the phase A3 when practically the air VPD became similar in both treatments (Fig. 3, Table 4).

Table 4 and Fig. 4 show that the transpiration rates for both treatments were not significantly different ($P < 0.05$) before the irrigation during phase B1. However, both treatments were significantly different before the irrigation during phase B2. On average, the transpiration rate decrease for the moist treatment was 0.16 mm h^{-1} (Fig. 4, Table 4) in each pivot arm portion. Monteith and Unsworth (2008) indicate that all the recorded values in a particular weather station, such as air temperature, relative humidity, and wind are influenced by vegetation type and characteristics that are at a distance of about 100 times the average crop height, mainly in the direction where the wind comes. As the pivot arm is continuously moving over the field, the areas nearby the transect AC have been irrigated already when the pivot arm arrives to that transect. Thus, the transpiration and VPD decreases observed before the irrigation water droplets moistened the transect AC were likely due to the effect of the microclimatic changes in these nearby areas. The influence of the predominant wind direction on the length of phase B2 is difficult to analyze because the incidence angle of wind on the pivot arm is continuously changing due to the rotation movement of the pivot. Nevertheless, the duration of phase B2 was somewhat longer for the monitored irrigation events showing east (E) predominant wind direction during that phase compared to irrigation events showing west (W) or southwest (SW) predominant wind direction (Table 5). This difference would have been even larger if the irrigation event on 13 August (the windiest by large) would have not been taken into account. According to Figure 1, east winds blow over recently irrigated field areas towards the pivot arm and the transect while west or southwest winds blow against the pivot arm rotation over field areas that have been irrigated some time before and therefore should be less humid.

The transpiration decrease in the moist treatment was greater during (phase Du) the irrigation of transect AC than that observed in the phase B2 (Fig. 4, Table 4). On average, this decrease was about 0.22-0.27 mm h^{-1} and quite similar for the three monitored pivot arm portions. Accounting for the duration of the irrigation of transect AC, the average total transpiration for the moist treatment was 0.78 mm (pivot arm portion 2), 0.34 mm (pivot arm portion 4), and 0.26 mm (pivot arm portion 5). This was about 36% (pivot arm portion 2) and 30% (pivot arm portions 4, 5) less than the average total transpiration for the dry treatment of 1.23, 0.49, and 0.38 mm h^{-1} for pivot arm portions 2, 4 and 5, respectively. Thus, the transpiration reduction was slightly greater for the pivot arm portion closer to center of the pivot as irrigation in this spot lasted longer. Tolk et al. (1995), using a lateral move sprinkler irrigation system, reported a transpiration reduction similar to the observed in this work, while the transpiration reduction during irrigation in solid-set sprinkler systems reported by Martínez-Cob et al. (2008) was greater. These differences likely were due to the duration of the irrigation, which was longer in the work of Martínez-Cob et al. (2008).

The transpiration decrease for the moist treatment just after the irrigation (phase A1) was 0.26-0.34 mm h^{-1}, slightly greater than that observed during the irrigation (Fig. 4, Table 4). Similar transpiration reductions were observed in all three pivot arm locations. Accounting for the duration of this phase, the average total transpiration for the moist treatment was 0.45 mm (pivot arm portion 2), 0.69 mm (pivot arm portion 4), and 0.61 mm (pivot arm portion 5), about 38, 39 and 29% less than the average total transpiration for the dry treatment of 0.72, 1.13, and 0.86 mm for pivot arm portions 2, 4 and 5, respectively. These results are different from those reported in previous works (Tolk et al. 1995; Martínez-Cob et al. 2008) that found lower transpiration reduction after the irrigation than during the irrigation. The work of Tolk et al. (1995) was done with a linear lateral move but irrigation of the field was completed in two hours. The work of Martínez-Cob et al. (2008) was done on a solid-set system and irrigation lasted for 2 to 3 hours and there were not nearby irrigated areas after the irrigation finished. Due to the rotation movement of the center pivot it is clear that the pivot arm was irrigating nearby areas during some time after passing for the transect AC. Consequently, the microclimatic changes in the nearby areas to the transect AC (both sides) were also affecting the transpiration rates in the transect AC. Thus, the transpiration reduction in phase A1 was slightly greater than found during the irrigation and it lasted longer in the pivot than in solid-set systems (Martínez-Cob et al. 2008; Cavero et al. 2009).

The corn transpiration rates for the moist treatment in phase A2 after the irrigation were about 17% (pivot arm portions 2 and 4) and 16% (pivot arm portion 5) significantly lower than those for the dry treatment (Table 4, Fig. 4) but the average reduction was lower (<0.14 mm h^{-1}). Finally, in phase A3 after the irrigation, the differences among the treatments, although significant ($P < 0.05$), were only 0.02 mm h^{-1} on average and thus should be considered negligible (Table 4, Fig. 4).

Fig 5 shows the average corn transpiration rates versus the air VPD measured at each meteorological station (three at the transect AC, moist treatment, and one at spot D, dry treatment) before (B2 phase), during (Du phase) and after (A1 phase) the center pivot sprinkler irrigation events. There was a moderate to high relationship between these two variables at both treatments according to the corresponding coefficients of determination (r^2). These were greater during the irrigation events (phase Du), ranging from 0.75 to 0.82, than before (phase B2) and after (phase A1) the irrigations, ranging from 0.53 to 0.56 except for the pivot arm portion 4 during phase B2 (r^2=0.69). It is clear that the direct effect of sprinkler irrigation is the increase of the air relative humidity and thus the decrease of air VPD resulting in a concomitant decrease of corn transpiration rate and this effect is greater during the irrigation event. Before and after the irrigation event this effect still exists but to a lesser extent.

Likewise, the magnitude of the decrease of air VPD and corn transpiration rates during the irrigation (phase Du) was dependent on the general meteorological conditions in the study area expressed by the VPD at spot D. Table 6 lists the results of the linear regressions between the decreases of air VPD and corn transpiration at each measurement spot of the transect AC versus the average air VPD recorded at the spot D during the phase Du. There was a strong relationship between the decrease of air VPD at the measurement spots of transect AC and the VPD at spot D. That relationship was not so strong (lower r^2) for the case of the decrease of transpiration. The decrease of air VPD and corn transpiration was greater as the air

VPD at the dry treatment increased. Martínez-Cob et al. (2008) reported similar relationships.

Martínez-Cob et al. (2008) reported that the transpiration reduction for the moist treatment lasted less than 1 h after the irrigation in solid-set sprinkler systems. However, the average duration of this reduction in the center pivot studied in this work was longer. Moreover, the largest differences among the different pivot arm portions were found in the duration of transpiration reduction after the irrigation. Thus, the sum of the average duration of phases A1 and A2 (when differences among the treatments were above the resolution of the sap flow gauges used) for the monitored irrigation events was 1.8 h (pivot arm portion 2), 2.6 h (pivot arm portion 4), and 2.4 h (pivot arm portion 5) (Table 4). This lower duration of transpiration reduction after the irrigation in the pivot arm 2 could be related with the lower instantaneous irrigation application rate in this part of the pivot. In any case, these effects were also affected by the meteorological conditions of each irrigation event, such as the average vapour pressure deficit of the air, and the wind speed and direction due to the influence of the irrigated nearby areas. The variability of these meteorological conditions led to the high variability of the duration of the transpiration reduction (high coefficients of variation, Table 4). The monitored irrigation events showing E predominant wind direction had a longer duration of phase A1 than the irrigation event showing S predominant wind direction during that phase (Table 5). The duration of phase A1 for the irrigation events showing SW predominant wind direction was only slightly shorter than that for irrigation events showing E predominant wind direction, particularly on 13 August, the windiest by large of all studied irrigation events (Tables 2 and 5). The magnitude of the decreases of corn transpiration and air VPD was much less affected by the wind direction than by the general meteorological conditions expressed by the air VPD at the spot D (Table 5, Figure 5).

Table 7 shows the values of SEL_n calculated for each monitored irrigation event using the equations (5) to (9). The average values of $WDEL_g$ were 13% (pivot arm portion 2), 11% (pivot arm portion 4) and 10% (pivot arm portion 5) of the applied water. The coefficients of variation of the water collected at the catch cans ranged from 6 to 14 % for most of irrigation events and pivot arm portions suggesting that uncertainty of the $WDEL_g$ measurements was relatively small (Table 3). Thus, there was a slight decrease of $WDEL_g$ towards the outer part of the pivot. The highest values of $WDEL_g$ in the different pivot arm portions were recorded on 13 August, the windiest day (Table 2): 25 % (pivot arm portion 2), 28 % (pivot arm portion 4), and 26 % (pivot arm portion 5) of the applied water. These average $WDEL_g$ were similar to those reported for daytime sprinkler irrigation in previous works in semiarid areas for moving systems (Tolk et al. 1995; Playán et al. 2005; Ortiz et al. 2009) but lower than those found in solid-set systems (Dechmi et al. 2003; Martínez-Cob et al. 2008).

On average, the estimated reduction of evapotranspiration during the irrigation of the transect AC in the 7 monitored irrigation events was 0.33 mm (pivot arm portion 2), 0.18 mm (pivot arm portion 4), and 0.17 mm (pivot arm portion 5) (Table 7). The corresponding $WDEL_n$ estimated from equation (6) were: 1.5 mm (pivot arm portion 2), 1.3 mm (pivot arm portions 4 and 5), which amounted 11% (pivot arm portion 2), 10% (pivot arm portion 4), and 9% (pivot arm portion 5) of the applied water (Table

7). Thus, the evapotranspiration reduction due to irrigation represented an 18% (pivot arm portion 2) and 12% (pivot arm portions 4 and 5) of $WDEL_g$. In terms of the applied water, the evapotranspiration reduction due to irrigation amounted to 2.3 % (pivot arm portion 2) and 1.3 % (pivot arm portions 4 and 5). Considering these values and those of Martínez-Cob et al (2008) in solid-set systems, it seems that, during sprinkler irrigation, as the $WDEL_g$ increases the reduction of ET (due to the reduction of plant transpiration) increases.

As discussed previously, IL_n is the balance between the evaporation of intercepted water and the reduction of the transpiration after the irrigation, i.e. the difference between the evapotranspiration rates of the moist and dry treatments. For a solid-set sprinkler system, Martínez-Cob et al. (2008) found that this difference between the evapotranspiration rates of both treatments was limited to a period of 1 h after the irrigation finished. Tolk et al. (1995) also found similar results for a lateral-move sprinkler system. As evapotranspiration rates were not measured in this work, it was assumed, as a rough approximation, a period of 1 h after the irrigation event in order to calculate the IL_n. After that hour, it was considered that the observed corn transpiration reduction was completely compensated by the evaporation of intercepted water such that IL_n were nil. Then, equation (9) was only applied during the first hour after the irrigation event. The IL_n estimated from equation (9) was on average 0.3 mm in all the pivot arm portions monitored (Table 7), similar to those values reported by Tolk et al. (1995) and Martínez-Cob et al. (2008).

Assuming the estimated IL_n values, the average SEL_n values were 1.8 mm (pivot arm portion 2) and 1.6 mm (pivot arm portions 4 and 5) (Table 7). Thus, the SEL_n would represent 13%, 12%, and 11% of the applied water in the pivot arm portion 2, 4 and 5, respectively (Table 7). These SEL_n values were even slightly greater than the observed $WDEL_g$ values. Estimation of water application efficiency requires knowledge of the SEL_n (McNaughton, 1981; Tolk et al., 1995; Martínez-Cob et al., 2008). However, the results listed on Table 7 suggest that, although corn transpiration was reduced during the irrigation with center pivot, the $WDEL_g$ could be a good estimate of SEL_n. The estimates of SEL_n listed in Table 7 suggest that the net sprinkler and evaporation losses in pivots with impact sprinklers are relatively small in terms of the applied water and slightly decrease along the pivot arm due to the differences in $WDEL_g$ and the magnitude and duration of the transpiration reduction during and after the irrigation events in the different pivot arm portions. Due to the rough estimates of some terms in equations (7) to (9), these results must be considered as preliminary and further research is required, mainly for measuring the evapotranspiration rather than transpiration rates during and after the irrigation events.

There is some uncertainty regarding to the calculation of IL_n value. In this paper, the increase of evapotranspiration in the moist treatment 1 hour after the irrigation events reported by Martínez-Cob et al. (2008) has been used to estimate the IL_n, resulting in a value of about 2 % of the applied water. However, other authors reported that IL_n for corn can range between 5 and 7 % for application depth between 15 and 25 mm in lateral-move sprinkler irrigation systems (Tolk et al. 1995).

There is a need for further research to quantify the magnitude and duration of the plants transpiration reduction for center pivot systems using other types of sprinklers, for instance, rotating spray plate sprinklers, because the WDEL and the magnitude or duration of the possible transpiration reduction could be different because of the way the water is applied, closer to the crop canopy and to the ground.

4. CONCLUSIONS

During irrigation of corn using a center pivot system with impact sprinklers plant transpiration was reduced by 36% for pivot arm portion 2 (close to the center) and 30% for pivot arm portions 4 and 5 (far from the center). Some transpiration reduction was observed before water droplets began to moisten the corn plants. After the pivot arm has passed by the studied area transpiration continued to be reduced during 1.8 h (pivot arm portion 2), 2.6 h (pivot arm portion 4) and 2.4 h (pivot arm portion 5), and amounted 27 % (pivot arm portion 2), 29 % (pivot arm portion 4), and 22 % (pivot arm portion 5).

The measured gross wind drift and evaporation losses ($WDEL_g$) were 13, 11 and 10% of applied water for pivot arm portion 2, 4 and 5, respectively. When discounting the evapotranspiration reduction during the irrigation (estimated from the measured transpiration reduction), the net wind drift and evaporation losses ($WDEL_n$) were slightly lower: 11, 10 and 9% of the applied water in the pivot arm portions 2, 4 and 5.

The net sprinkler evaporation losses (SEL_n) amounted 13% (pivot arm portion 2), 12% (pivot arm portion 4), and 11% (pivot arm portion 5) of the applied water. These SEL_n values were similar to the observed $WDEL_g$ values so in center pivots with impact sprinklers the easily measured $WDEL_g$ is a good estimate of total evaporation losses. Thus for these systems, it would not be required to estimate SEL_n for estimation of water application efficiency.

Further research is required for center pivot systems using other type of water emitters.

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FIGURE CAPTIONS

Fig. 1. Layout of the experimental plot. A to C, sap flow and meteorological stations along the transect AC (moist treatment). D, sap flow and meteorological station at the dry treatment. Mp, pivot arm. P_r, irrigation pressure transducers. R_{1-6}, radius from each pivot tower to the center pivot. M, the movement of the center pivot in counter clock wise direction. (SIGPAC 2011).

Fig. 2. 10-min average corn transpiration rates and vapour pressure deficit of air (VPD) at pivot arm portions 2, 4 and 5, from 2 h before until 6 h after the irrigation event monitored on 31 July. MT, moist treatment. DT, dry treatment. The vertical continuous lines indicate the start and the end of the irrigation over the transect AC (water droplets falling over the plants). The vertical dashed lines indicate the periods during which transpiration rates were different between the two treatments. Du, irrigation of the transect AC; B1 and B2, before the irrigation; A1 to A3, after the irrigation. The “Material and methods” section describes how these different phases were established.

Fig. 3. Vapour pressure deficit (VPD) of the air measured in the dry (DT) treatment versus VPD of the air measured in the moist (MT) treatment during the seven monitored irrigation events. B1 and B2, before irrigation; Du, during irrigation; A1 to A3, after irrigation. PAP, Pivot Arm Portion.

Fig. 4. Corn transpiration rates in the seven monitored irrigation events for the dry (DT) treatment versus those in the moist (MT) treatment in the different pivot arm

portions (PAP). B1 and B2, before the irrigation; Du, during the irrigation; A1 to A3, after the irrigation.

Fig. 5. Relationship between the average transpiration rates of maize and the average VPD of the air measured before (B2 phase), during (Du phase) and after (A1 phase) the center pivot sprinkler irrigation events for the moist (MT) and dry (DT) treatments in the different pivot arm portions (PAP).

APPENDIX A. DETERMINATION OF CORN EVAPOTRANSPIRATION AT DRY TREATMENT

The 5-min averages of the meteorological variables recorded at spot D were used to estimate corn evapotranspiration at the dry treatment, ET_{DT}, during each monitored irrigation event using the Penman-Monteith equation directly applied to the corn crop (Allen et al. 1996):

$$ET_{DT} = \frac{300}{10^6 \lambda} \frac{\Delta(R_n - G) + \rho_a c_p VPD / r_a}{\Delta + \gamma\left(1 + \frac{r_c}{r_a}\right)} \quad (10)$$

where: λ, latent heat of vaporization (MJ Kg^{-1}); R_n, net radiation (W m^{-2}); G, soil heat flux (W m^{-2}); Δ, slope of the saturation vapour pressure curve versus the temperature (kPa $^{o}C^{-1}$); ρ_a, air density (Kg m^{-3}); c_p, specific heat of the air (J Kg^{-1} $^{o}C^{-1}$); VPD, vapour pressure deficit (kPa); r_a, aerodynamic resistance (s m^{-1}); r_c, bulk stomatal (canopy) resistance (s m^{-1}); γ, psychrometric constant (kPa $^{o}C^{-1}$).

The variables λ, Δ, ρ_a, γ, and c_p were estimated from measured air temperature and relative humidity following standard procedures described by Allen et al. (1998). G was estimated from net radiation following Allen et al. (1996):

$$G = 0.4\, e^{-0.5 LAI} R_n \quad (11)$$

where LAI is the daily leaf area index estimated from measured crop height as suggested by Allen et al. (1996).

The aerodynamic resistance r_a (s m^{-1}) to vapour transfer was estimated following Allen et al. (1996):

$$r_a = \frac{\left[\ln\left(\frac{z_u - d}{z_{0m}}\right)\right]\left[\ln\left(\frac{z_h - d}{z_{0h}}\right)\right]}{k^2\, u_{zu}} \qquad (12)$$

where: u_{zu} is the wind speed (m s^{-1}) measured at a height z_u; k is the von Karman's constant (0.41); z_u and z_h are the measurement heights (m) above ground of wind speed, and air temperature and relative humidity, respectively; and d, z_{0m}, and z_{0h} (all three in m) are the zero-plane displacement and the roughness lengths for momentum and heat transfer, respectively, estimated (daily) as a function of crop height (h_c) and LAI following Farahani and Bausch (1995) and Kjelgaard et al. (1994):

$$d = 1.1\, h_c \ln\left[1 + (c_d\, LAI)^{1/4}\right] \qquad (13)$$

$$z_{om} = 0.3\, h_c\, (1 - d/h_c) \qquad (14)$$

and,

$$z_{0h} = 0.2\, z_{0m} \qquad (15)$$

where c_d is the mean drag coefficient for individual leaves (0.07). Eq. (14) was chosen as the product (c_d LAI) was above 0.2 (Farahani and Bausch 1995) due to the LAI values around 4.0 estimated during the monitoring period as crop height was about 2.5 m.

The bulk canopy resistance (s m^{-1}), r_c, was estimated following Farahani and Bausch (1995):

$$r_c = \left\{ c_0\,LAI + \frac{c_1}{c_2\,C}\ln\left[\frac{1+c_2\,C\;R_s}{1+c_2\,C\;R_s\exp(-C\;LAI)}\right]\right\}^{-1} \tag{16}$$

where: R_s is the incoming solar radiation (W m^{-2}) estimated from the linear regression between the measured net radiation at the spot D and the incoming solar radiation measured in a nearby weather station also located at Valfarta; c_0 is the minimum stomatal conductance (0.0005 m s^{-1}); c_1 and c_2 are constants defined as c_1 = 3.2E-5 m s^{-1} and c_2 = 5.7E-5 m s^{-1}; and C is the light extinction coefficient, assumed to be 0.50 as suggested by Cavero et al. (1999, 2000) for similar crop and climatic conditions to those in this work.

Table 1. General characteristics of the center pivot system.

Pivot arm portion	Number of sprinklers			Nozzle diameters	Distance[a]	Spacing between sprinklers
	With 1 nozzle	With 2 nozzles	Total			
				mm	m	m
1	5		5	2.8 - 4.8	48.3	9.3
2	7		7	4.8 - 5.4	97.8	7.0
3	2	6	8	4.2 - 5.8	147.2	6.2
4		8	8	4.8 - 6.0	196.6	6.2
5	12	4	16	4.2 - 6.0	246.1	3.1
6		16	16	4.4 - 5.6	295.5	3.1
Wing		8	8	4.6 - 5.4	321.1	2.9

[a] Distance of the corresponding tower to the central axis of the pivot.

Table 2. Average meteorological conditions recorded during the monitored irrigations events at the nearby weather station of Valfarta[a].

Date	Air temperature	Air vapour pressure deficit	Wind speed	Solar radiation
	ºC	kPa	m s^{-1}	W m^{-2}
July 24	28.0	1.9	2.0	742
July 31	32.5	3.6	1.5	880
August 6	29.9	2.6	1.8	772
August 13	22.8	1.7	3.5	723
August 21	27.4	1.7	2.0	780
August 28	26.6	1.6	0.9	768
September 10	27.3	1.8	1.6	651

[a] It belongs to the Spanish Irrigation Advisory System (http://www.marm.es/es/agua/temas/observatorio-del-regadio-espanol/sistema-de-informacion-agroclimatica-para-el-regadio/)

Table 3. General characteristics of the monitored irrigation events in the different parts of the center pivot during the period that the pivot arm was moving over the transect AC (phase Du).

Pivot arm portion	Date	Starting time[a]	Duration	Pressure		Applied water (I_s)	Collected water depth (I_{cc})	
				Mean	CV[b]		Mean	CV
	(dd/mm)	---------- h -----------		kPa	%	mm	mm	%
2	24/07	08:25	1.70	208		14.6	13.0	18
	31/07	09:35	1.62	218	0.8	14.9	13.4	15
	06/08	09:00	1.62	214	0.5	14.8	12.6	14
	13/08	09:05	1.55	216	0.6	14.2	10.6	19
	21/08	09:20	1.55	198	1.0	13.6	12.8	14
	28/08	09:45	1.62	207	1.0	14.5	12.3	12
	10/09	10:15	1.62	208	3.3	14.6	13.3	10
4	24/07	08:40	0.62	193	2.2	13.6	11.9	7
	31/07	09:55	0.60	197	1.6	13.8	12.3	11
	06/08	09:15	0.60	194	1.9	13.6	12.3	10
	13/08	09:20	0.57	197	1.0	13.1	9.5	13
	21/08	09:35	0.57	177	2.4	12.4	11.9	6
	28/08	10:00	0.60	181	1.9	13.2	11.9	8
	10/09	10:30	0.60	194	1.6	13.7	12.9	7
5	24/07	08:40	0.50	195	0.3	14.4	13.3	12
	31/07	09:55	0.48	199	1.3	14.5	13.4	14
	06/08	09:20	0.48	197	1.5	14.5	12.9	14
	13/08	09:20	0.45	200	0.7	13.9	10.4	13
	21/08	09:40	0.45	174	0.8	13.0	12.6	10
	28/08	10:00	0.48	179	0.9	13.8	12.6	12
	10/09	10:30	0.48	202	0.6	14.7	13.3	10

[a] Greenwich Mean Time.
[b] CV, coefficient of variation.

Table 4. Average maize transpiration rate (T) and vapour pressure deficit of the air (VPD) of moist (MT) and dry (DT) treatments and the corresponding differences between them before (phases B1 and B2), during (Du) and after (phases A1, A2 and A3) the monitored irrigation events in the different pivot arm portion (PAP). The duration of these phases is also listed.

Phase	PAP	N[a]	Transpiration			VPD			Duration	
			T_{MT}	T_{DT}	T_{MT}-T_{DT}	VPD_{MT}	VPD_{DT}	VPD_{MT}-VPD_{DT}	mean	CV[b]
			--------- mm h^{-1} -------			-------------- kPa ------------			h	%
B1	2	7	0.38	0.39	-0.01 ^{ns}	0.89	0.96	-0.08 ^{s}	1.0	53
	4	7	0.38	0.39	-0.01 ^{ns}	0.94	1.00	-0.06 ^{s}	0.7	60
	5	7	0.46	0.48	-0.02 ^{ns}	0.92	0.98	-0.06 ^{s}	1.7	59
B2	2	3	0.48	0.63	-0.15 ^{s}	1.07	1.31	-0.24 ^{s}	1.0	76
	4	7	0.41	0.60	-0.18 ^{s}	1.02	1.20	-0.18 ^{s}	1.0	66
	5	3	0.49	0.64	-0.16 ^{s}	1.15	1.38	-0.23 ^{s}	1.2	75
Du	2	7	0.48	0.75	-0.27 ^{s}	0.88	1.42	-0.54 ^{s}	1.6	4
	4	7	0.51	0.73	-0.22 ^{s}	0.70	1.38	-0.68 ^{s}	0.7	0
	5	7	0.53	0.76	-0.23 ^{s}	0.72	1.34	-0.62 ^{s}	0.5	0
A1	2	7	0.54	0.86	-0.33 ^{s}	1.38	1.74	-0.36 ^{s}	0.8	65
	4	6	0.53	0.87	-0.34 ^{s}	1.23	1.62	-0.39 ^{s}	1.3	37
	5	5	0.63	0.89	-0.26 ^{s}	1.23	1.68	-0.45 ^{s}	1.0	56
A2	2	7	0.71	0.85	-0.14 ^{s}	2.04	2.23	-0.19 ^{s}	1.0	88
	4	7	0.65	0.79	-0.14 ^{s}	2.00	2.20	-0.20 ^{s}	1.3	52
	5	7	0.69	0.82	-0.13 ^{s}	1.86	2.03	-0.17 ^{s}	1.4	53
A3	2	7	0.72	0.74	-0.02 ^{s}	2.25	2.35	-0.10 ^{s}	2.6	22
	4	7	0.68	0.70	-0.02 ^{s}	2.17	2.26	-0.10 ^{s}	3.6	17
	5	7	0.67	0.70	-0.02 ^{s}	2.17	2.25	-0.08 ^{s}	4.1	19

[a] N, number of irrigation events.

[b] CV, coefficient of variation.

For each variable, phase and pivot arm portion, differences between the moist and dry treatments were non significant (^{ns}) or significant (^{s}) according to a paired t test and a level of significance of P = 0.05.

Table 5. Average reduction of vapour pressure deficit of the air (ΔVPD) and maize transpiration (ΔT) and average duration of that reduction for the different monitored irrigation events grouped according to the predominant wind direction (WD) before (phase B2) and after (phase A1) the irrigation events. Average wind speed for those groups is also listed.

Phase	WD[a]	Date	Wind Speed	Observed decreases		
				ΔVPD	ΔT	Duration
		dd/m	m s^{-1}	KPa	mmh^{-1}	h
B2	E	24/7, 31/7, 06/8, 21/8, 28/8	1.7	0.20	0.17	1.0
	SW	10/9, 13/8	2.9	0.24	0.14	0.8
A1	E	24/7, 31/7, 06/8, 21/8	1.6	0.41	0.35	1.2
	S	28/8	0.9	0.49	0.26	0.4
	SW	10/9, 13/8	2.4	0.29	0.26	1.0

[a] Recorded at the nearby 'grass station': E, east (67.5 to 112.5°); S, south (157.5 to 202.5°); southwest, SW (202.5 to 247.5°); west, W (247.5 to 292.5°).

Table 6. Analysis of linear regression ($y=b_0+b_1 x$) between the VPD averages recorded at station D (independent variable x) and the average decreases of vapour pressure deficit (ΔVPD) and transpiration rate (ΔT) (dependent variables y) observed during the irrigation events (phase Du). b_0 and b_1, intercept and slope of the linear regression, respectively. r^2, coefficient of determination. PAP, pivot arm portion.

Variable Y	Variable X	PAP	Linear Regression		
			b_0	b_1	r^2
ΔVPD	VPD	2	-0.21	0.53	0.87
		4	-0.14	0.48	0.83
		5	-0.30	0.68	0.87
ΔT	VPD	2	-0.10	0.26	0.61
		4	-0.16	0.27	0.79
		5	0.07	0.12	0.51

Table 7. Irrigation applied water (I_s), evapotranspiration reduction during the irrigation $(ET_{red})_{di}$, gross and net wind drift and evaporation losses (WDEL), net interception losses (IL_n) and net sprinkler evaporation losses (SEL_n in mm and % of I_s) in the different irrigation events in the different parts of the center pivot.

Pivot arm portion	Date	I_s	$(ET_{red})_{di}$	WDEL Gross	WDEL Net	IL_n	SEL_n	SEL_n
		mm						%
2	July 24	14.6	0.25	1.5	1.3	0.3	1.6	11
	July 31	14.9	0.58	1.5	1.0	0.3	1.3	9
	August 6	14.8	0.47	2.2	1.8	0.3	2.1	14
	August 13	14.2	0.15	3.5	3.4	0.3	3.7	26
	August 21	13.6	0.31	0.7	0.4	0.3	0.7	5
	August 28	14.5	0.17	2.2	2.1	0.3	2.3	16
	September 10	14.6	0.07	1.2	1.2	0.2	1.4	9
	Mean	14.4	0.33	1.9	1.5	0.3	1.8	13
4	July 24	13.6	0.13	1.7	1.6	0.2	1.8	13
	July 31	13.8	0.37	1.4	1.0	0.3	1.4	10
	August 6	13.6	0.20	1.4	1.2	0.3	1.5	11
	August 13	13.1	0.14	3.6	3.5	0.3	3.8	29
	August 21	12.4	0.17	0.5	0.4	0.2	0.6	5
	August 28	13.2	0.14	1.3	1.2	0.2	1.4	11
	September 10	13.7	0.10	0.7	0.6	0.2	0.8	6
	Mean	13.3	0.18	1.5	1.3	0.3	1.6	12
5	July 24	14.4	0.12	1.1	1.0	0.2	1.3	9
	July 31	14.5	0.24	1.2	0.9	0.3	1.2	9
	August 6	14.5	0.16	1.6	1.4	0.3	1.7	12
	August 13	13.9	0.07	3.6	3.5	0.3	3.8	27
	August 21	13.0	0.07	0.3	0.3	0.3	0.5	4
	August 28	13.8	0.07	1.2	1.1	0.3	1.4	10
	September 10	14.7	0.04	1.4	1.3	0.2	1.5	11
	Mean	14.1	0.17	1.5	1.3	0.3	1.6	11

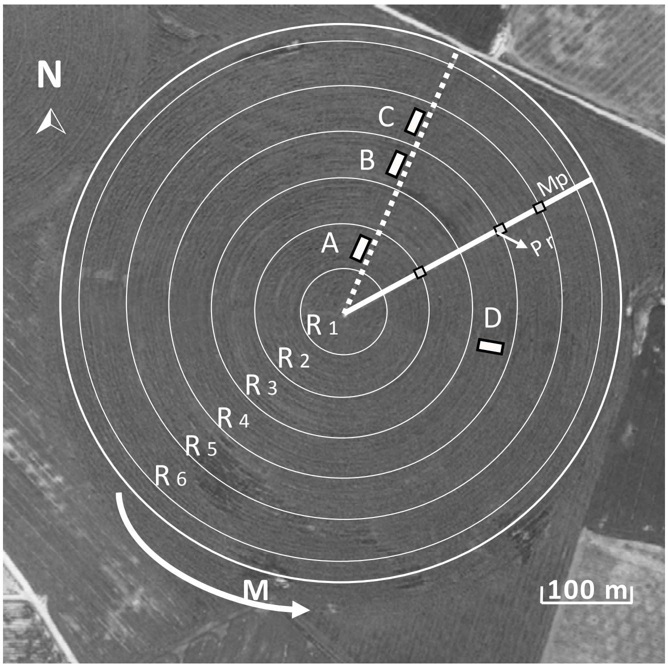

Figure 1. Layout of the experimental plot. A to C, sap flow and meteorological stations along the transect AC (moist treatment). D, sap flow and meteorological station at the dry treatment. Mp, pivot arm. P_r, irrigation pressure transducers. R_{1-6}, radius from each pivot tower to the center pivot. M, the movement of the center pivot in counter clock wise direction.

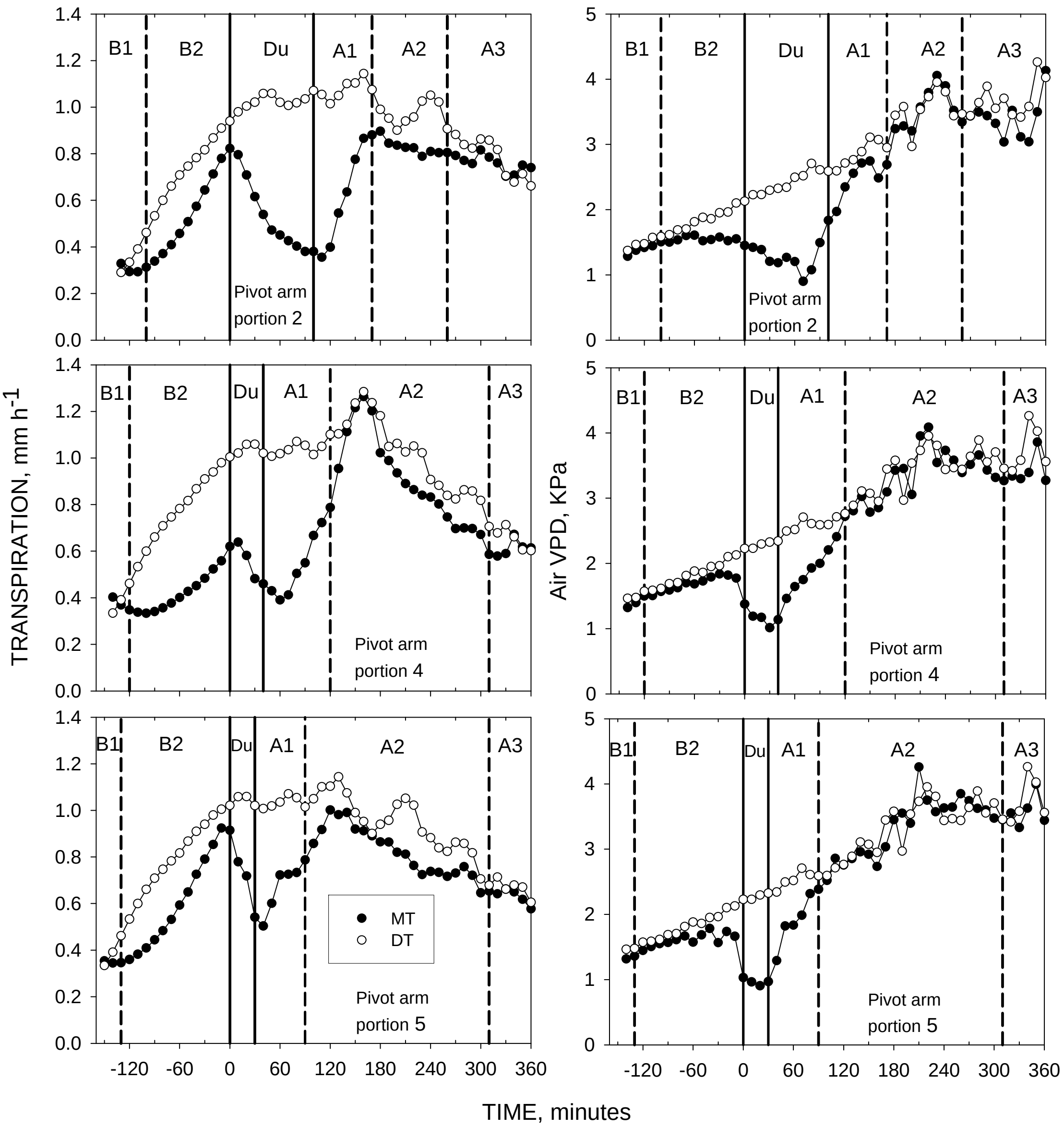

Fig. 2. 10-min average corn transpiration rates and vapour pressure deficit of air (VPD) at pivot arm portions 2, 4 and 5, from 2 h before until 6 h after the irrigation event monitored on 31 July. MT, moist treatment. DT, dry treatment. The vertical continuous lines indicate the start and the end of the irrigation over the transect AC (water droplets falling over the plants). The vertical dashed lines indicate the periods during which transpiration rates were different between the two treatments. Du, irrigation of the transect AC; B1 and B2, before the irrigation; A1 to A3, after the irrigation. The “Material and methods” section describes how these different phases were established.

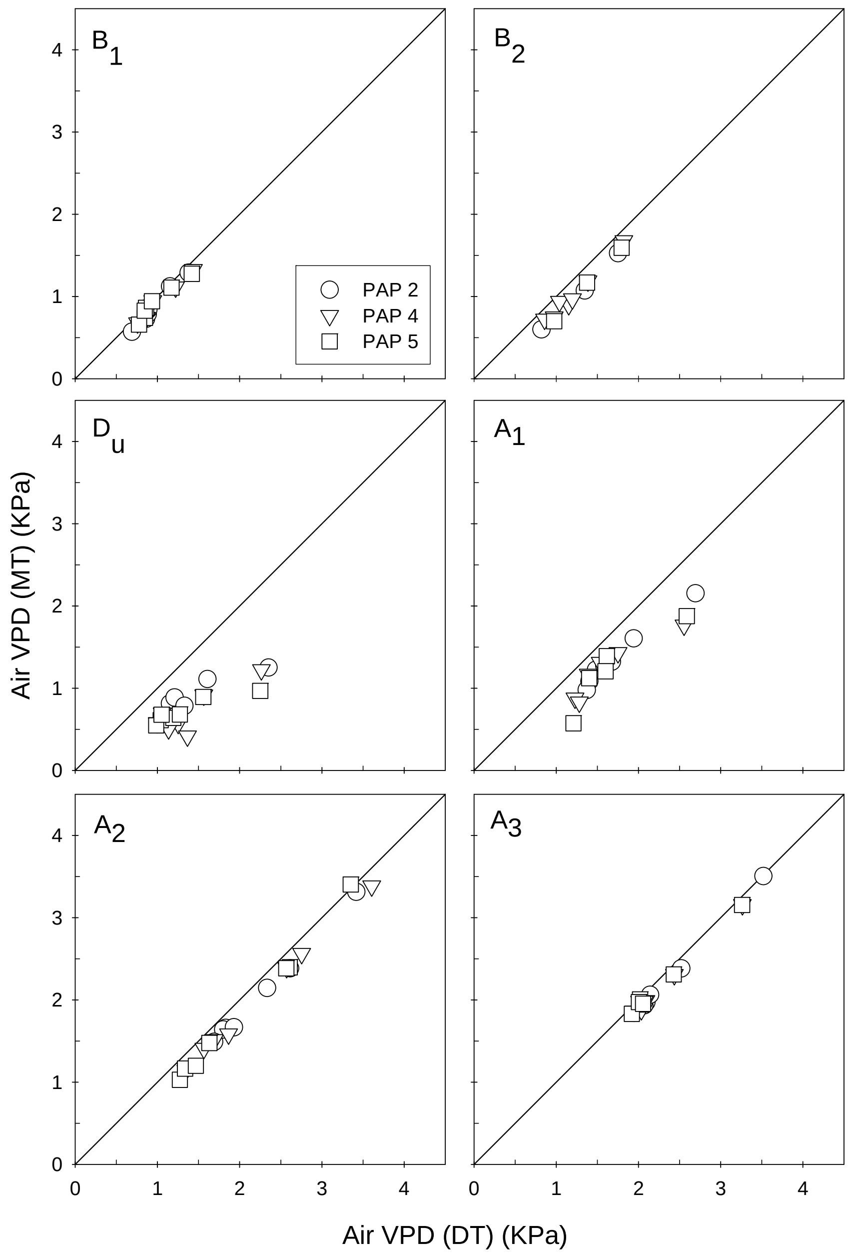

Fig. 3. Vapour pressure deficit (VPD) of the air measured in the *dry* (DT) treatment versus VPD of the air measured in the *moist* (MT) treatment during the seven monitored irrigation events. B_1 and B_2, before irrigation; D_u, during irrigation; A_1 to A_3, after irrigation. PAP, Pivot Arm Portion.

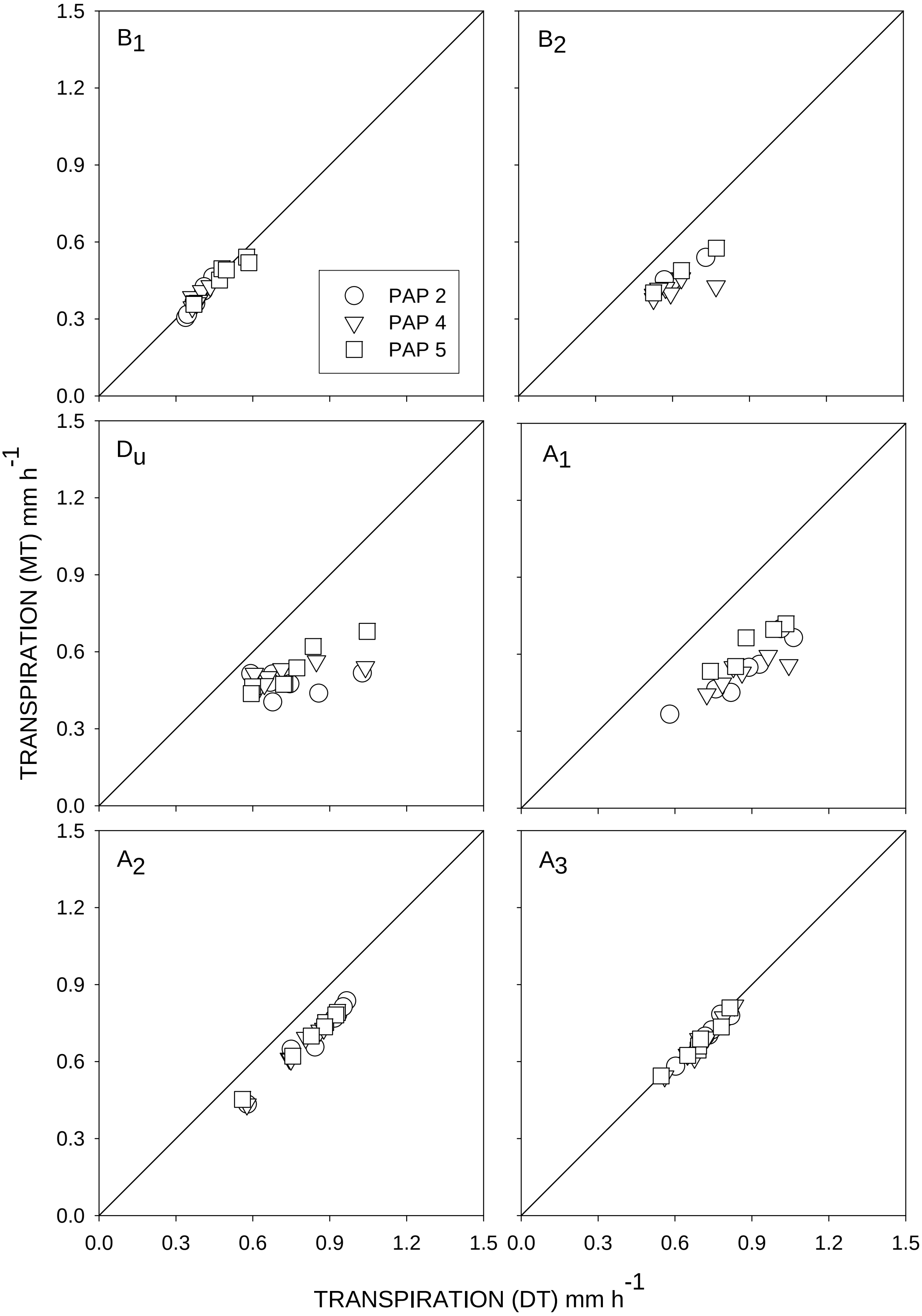

Fig. 4. Corn transpiration rates in the seven monitored irrigation events for the *dry* (DT) treatment versus those in the *moist* (MT) treatment in the different pivot arm portions (PAP). B1 and B2, before the irrigation; Du, during the irrigation; A1 to A3, after the irrigation.

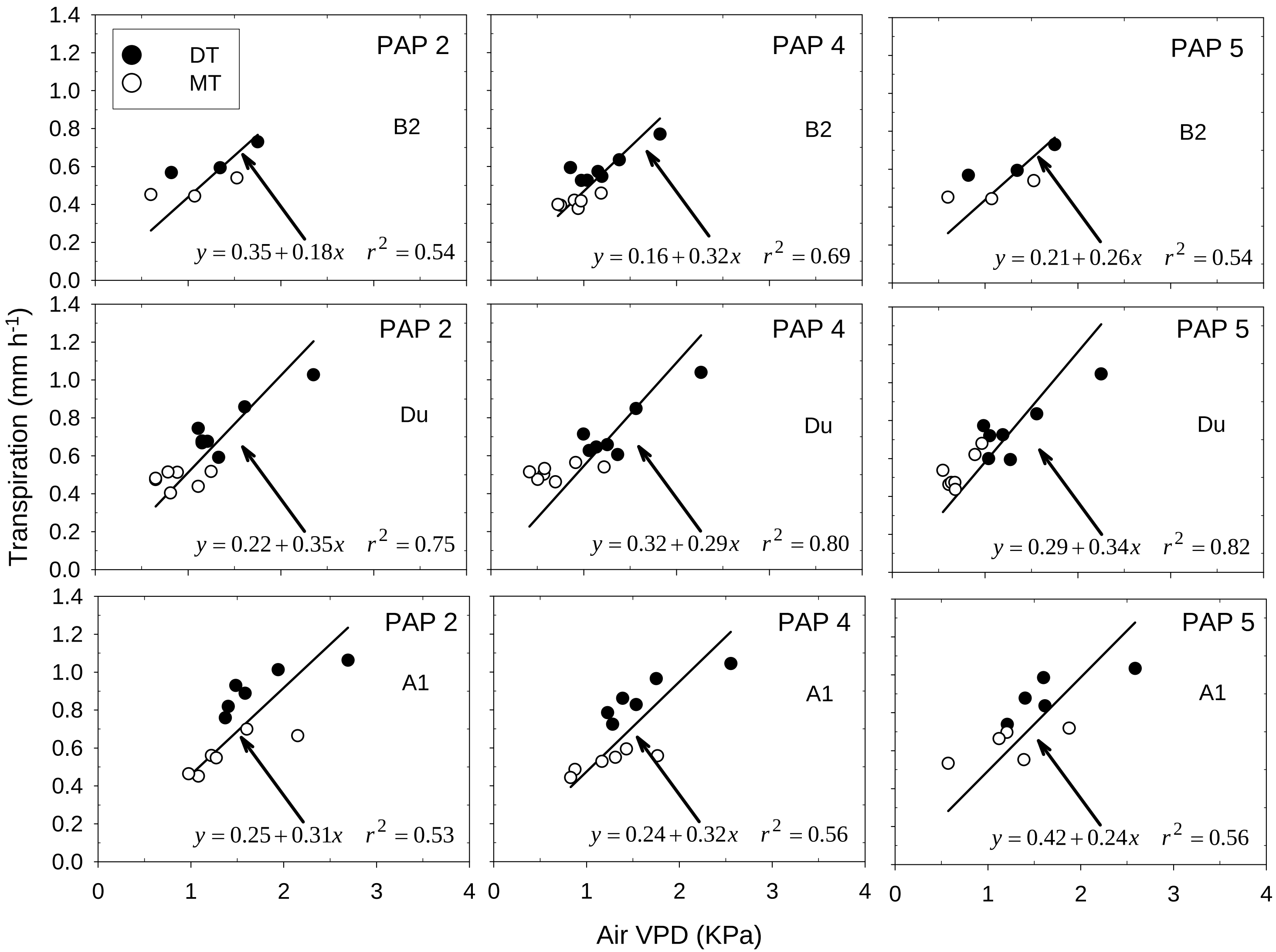

Fig. 5. Relationship between the average transpiration rates of maize and the average VPD of the air measured before (B2 phase), during (Du phase) and after (A1 phase) the center pivot sprinkler irrigation events for the *moist* (MT) and *dry* (DT) treatments in the different pivot arm portions (PAP).